INTEGRATED ROBOT-HUMAN CONTROL IN MINING OPERATIONS

Annual Progress Report
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Abstract

This report describes the results of the 2nd year of a research project on the implementation of a novel human-robot control system for hydraulic machinery. Sensor and valve re-calibration experiments were conducted to improve open loop machine control. A Cartesian control example was tested both in simulation and on the machine; the results are discussed in detail. The machine tests included open-loop as well as closed-loop motion control. Both methods worked reasonably well, due to the high-quality electro-hydraulic valves used on the experimental machine. Experiments on 3-D analysis of the bucket trajectory using marker tracking software are also presented with the results obtained.

Open-loop control is robustly stable and free of short-term dynamic problems, but it allows for drifting away from the desired motion kinematics of the machine. A novel, closed-loop control adjustment provides a remedy, while retaining much of the advantages of the open-loop control based on kinematics transformation.

Additional analysis of previously recorded, three-dimensional working trajectories of the bucket of large mine shovels was completed. The motion patterns, when transformed into a family of curves, serve as the basis for software-controlled machine kinematics transformation in the new human-robot control system.

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A. Introduction

A.1 Executive Summary

The general objective of the project is the evaluation of a new concept that integrates robotic control with human operator input in typical mining machines having multiple links and requiring coordinated motion of such links for the execution of cyclic, semi-repetitive operations.

The objective of the 2nd year of the research project was to evaluate the experimental robotized machine with the real-time man-machine control interface in a variety of tasks in laboratory tests, regarding the applicability and efficiency of its performance in typically cyclic and repetitive applications characteristic to surface mining operations.

The second year of the project included six tasks as follows:

1. *Mine Data Abstraction*: 3-D analysis of mine data collected in the first year of the project was performed using our camera calibration method and the Ariel Performance Analysis System (APAS). Mine data obtained using a stereo camera setup were processed in 3-D using APAS, to obtain bucket trajectories and bucket angles. Mine shovel trajectory data and knowledge gained throughout the trajectory analysis process continue to be used to aid in the development of parametric kinematics transformations, the basic paradigm of the research project.
2. *Software Kinematics:* A Cartesian kinematics transformation example was successfully tested both in simulation and on the experimental excavator. Both open-loop and closed-loop machine control versions of the Cartesian kinematics transformation were tested on the machine. 3-D machine motion recorded during machine tests shows satisfactory machine performance. As expected, the closed-loop version provides greater accuracy and repeatability of machine motion according to the software-generated kinematics. An innovative bucket steering kinematics transformation was also developed, which is expected to improve efficiency and accuracy of digging tasks, while reducing operator fatigue and machine wear.
3. *Software Trajectory:* A software-generated linear Cartesian trajectory family example was extensively tested. Numerous software modifications were made to improve performance of machine control. Additional trajectory families will be tested in year 3, and further software refinements will be made.
4. *Tests and Modifications:* The performance of the experimental excavator was evaluated using various control schemes, and the results were compared. Software modifications were applied as needed to improve performance. This task will continue as a significant part of year 3 under the scheduled task "Evaluation and Modification." Emphasis will shift from basic testing to more-advanced testing and performance evaluation.
5. *Other tasks:* A paper entitled "Digging Trajectory Analysis using Camera Vision" was submitted to the International Federation of Automatic Control for

publication related to the Workshop for Automation in Mining, Mineral and Metal Industry (IFAC-MMM'2006).

6. *Reporting:* Quarterly financial reports, quarterly PowerPoint briefing presentations, and the 2nd Annual Portfolio Review Presentation were completed.

B. Experiments

B.1 Bench Tests of the Experimental, Robotic Excavator

B.1.1 Sensor recalibration experiments

Position sensors on boom and arm were reinstalled for better protection during machine operation. A new position sensor for offset measurement was installed as shown in Figure 1. An experiment was conducted to measure minimum and maximum readings from the bucket, arm and boom sensors. Range of the sensors (minimum and maximum sensor voltage readings) was evenly divided into ten voltages (targeted output). The boom, arm and bucket were positioned to read the targeted sensor voltage output and a picture of the machine was recorded simultaneously with a digital camera. Five repetitions for the ten targeted positions of the sensors were completed. The data were utilized for sensor recalibration with respect to machine position using our new model based fitting algorithm [1]. Possible sensor interdependence was taken into consideration by simultaneously measuring three sensor outputs.

Boom sensor

Offset sensor

Figure 1: New sensor installation

B.1.2 Sensor Calibration and Data Acquisition System Verification Test

A system verification experiment was conducted to check the sensor calibration curves and the measurement system together. The machine links were moved through a sequence of different positions and the sensor outputs were recorded from the computer interface using the xPC Targetbox™ control / data acquisition computer. The machine positions were simultaneously recorded using a digital camera. As depicted in figures 23 and 24, the bucket pin and bucket edge trajectories of the machine, measured by the camera system, are quite well followed by the images generated based on the position readings obtained from the machine's sensors.

B.1.3 Improved Valve Calibration

The hydraulic control valves were re-calibrated using the test protocol applied and described previously in the first annual report. The results are shown in Figures 2 to 4 for the boom, arm and bucket valves.

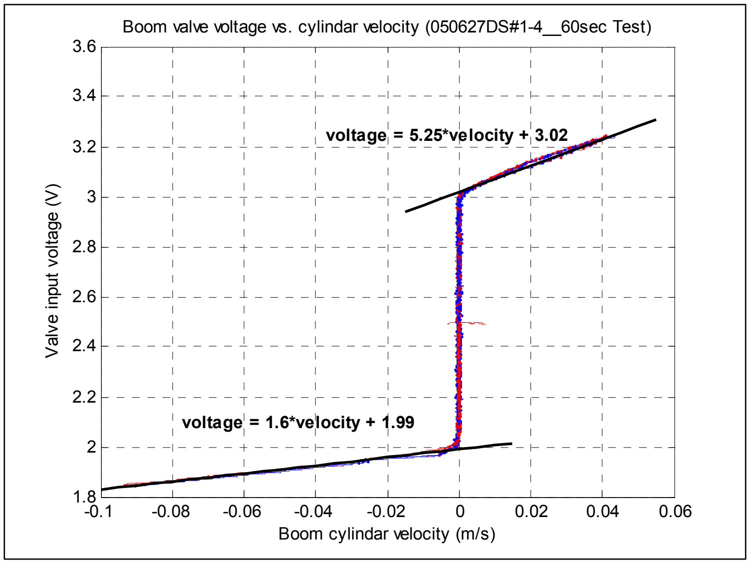

Figure 2: Boom Valve Calibration Curve

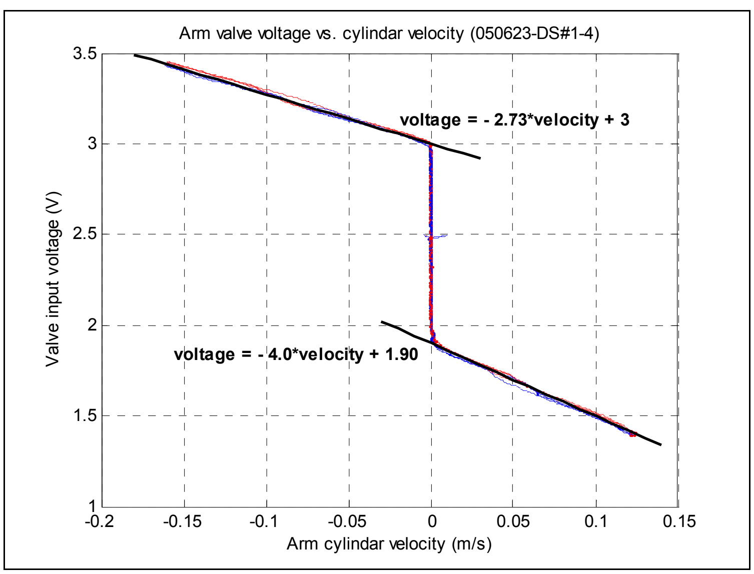

Figure 3: Arm Valve Calibration Curve

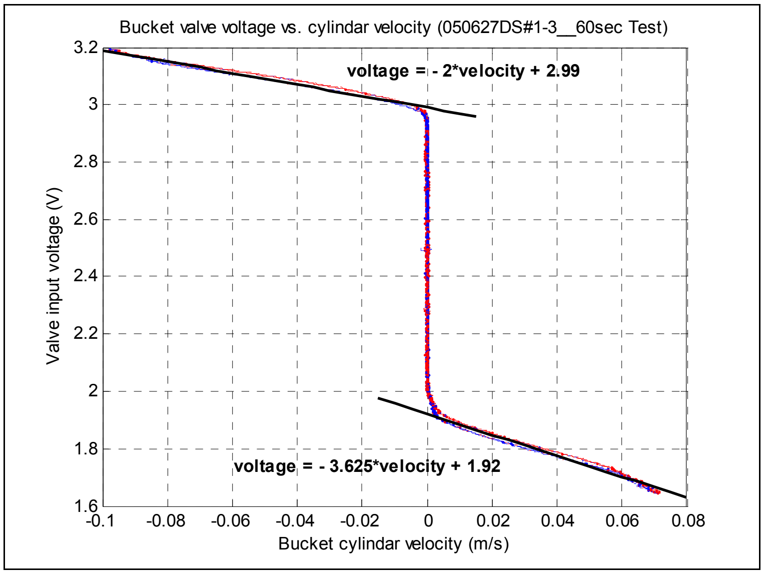

Figure 4: Bucket Valve Calibration Curve

B.1.4 Analytical Derivation of Sensor and Actuator Kinematics Equations [2]

For verification and comparison, an analytical derivation of the boom, arm and bucket actuator kinematics (and sensor calibration) functions was also performed. The actuator kinematics equations described the relationship between the joint variables (θ_1, θ_2, θ_3) and the lengths (L_{bm}, L_{am}, L_{bk}) of the hydraulic actuators. The linear position sensors were mounted parallel to the hydraulic actuators. Thus, the sensor output voltage was a simple (known) linear function of the actuator extension, based on the factory calibration constant of the sensor and the placement of each sensor on the actuator. This known relationship immediately gives the sensor calibration curves from the actuator kinematics functions.

The analytical relationship between the boom angle and the cylinder length was derived from the machine geometry (Figure 5) using simple trigonometric relationships. Constants in the equations are based on the Bobcat® 435 dimensions. The calibration curve obtained from (9) for the boom sensor was in fairly good agreement with the empirical calibration curve shown in Figure 5.3. Small discrepancies between the two functions are attributed to measurement error.

$$\theta_1 = 79.1792^\circ - \cos^{-1}\left(\frac{-L_{bm}{}^2 + 2.053}{1.042}\right) \qquad (9)$$

Similarly, the arm actuator kinematics was derived from the simple geometry shown in Figure 5. The arm sensor calibration curve obtained from (10) showed a small discrepancy with the empirical curve given in Figure 7, again attributed to measurement errors.

$$\theta_2 = \cos^{-1}\left(\frac{1.944 - L_{am}^2}{1.006}\right) - 0.457870^\circ \qquad (10)$$

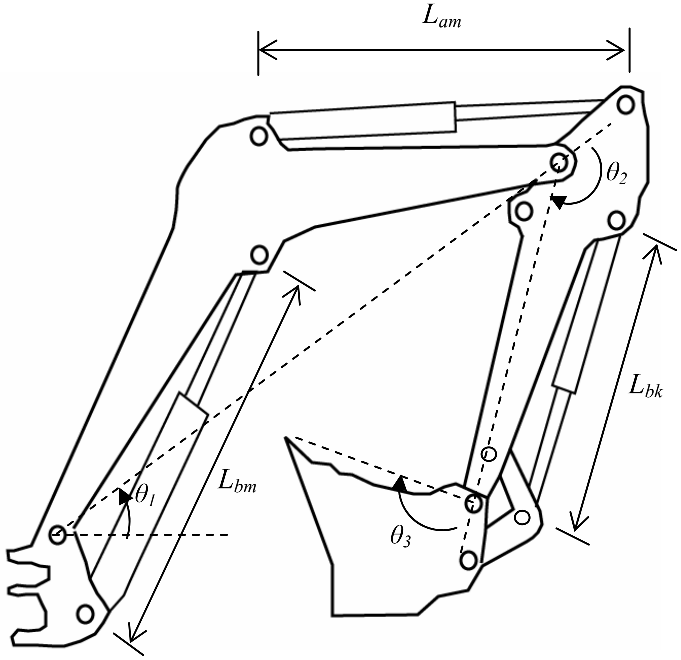

Figure 5: Analytical Actuator Kinematics: Relationship between Cylinder Lengths and Machine Link Angles

The bucket actuator linkage geometry is much more complicated than that of the boom and arm actuators. As a result, a simple solution to the analytical bucket kinematics cannot be easily obtained. The following system of non-linear functions (Equations 11 and 12) was derived to describe θ_3 as a function of the actuator extension, L_{bk}:

$$\theta_3 = \cos^{-1}\left(\frac{23.02^2 + m^2 - 31.99^2}{2.(23.02)m}\right) + \cos^{-1}\left(\frac{21.91^2 + m^2 - 31.43^2}{2(21.91)m}\right) - 80.812162 \tag{11}$$

$$\begin{gathered} m = \sqrt{31.99^2 + 23.02^2 - (2)(31.99)(23.02)\cos(b)} \\ b = 169.105705^\circ + \cos^{-1}\left(\frac{103.29^2 + 31.99^2 - L_{bk}^2}{2(103.29)(31.99)}\right) \end{gathered} \tag{12}$$

Substituting for m in (11) gives the forward actuator kinematics equation, $\theta_3 = f(L_{bk})$. Since this equation is rather complex, it is not clear if a closed form expression exists for the inverse function, $L_{bk} = f^{-1}(\theta_3)$. To circumvent this problem, an iterative numerical method was used to generate a large number of data points over the valid range of θ_3, and a polynomial fit was applied to the data, to obtain relatively simple expressions for both the forward and inverse functions.

B.2 Simulation

A linear simulation model of the machine for MATLAB/ Simulink was used for evaluation and refinement of the control algorithms. Simulated response helps to demonstrate feasibility of the approach. The block diagram of kinematics control and the machine model is shown in Figure 6 and Figure 7 respectively. The relationship between the kinematics of the "real" machine and the "virtual" machine is shown in Figure 8 for reference. The simulation uses machine kinematics and a software based model of the valves and sensors. Various combinations of proportional, integral and differential controllers were tested in simulation to provide accurate control of the excavator.

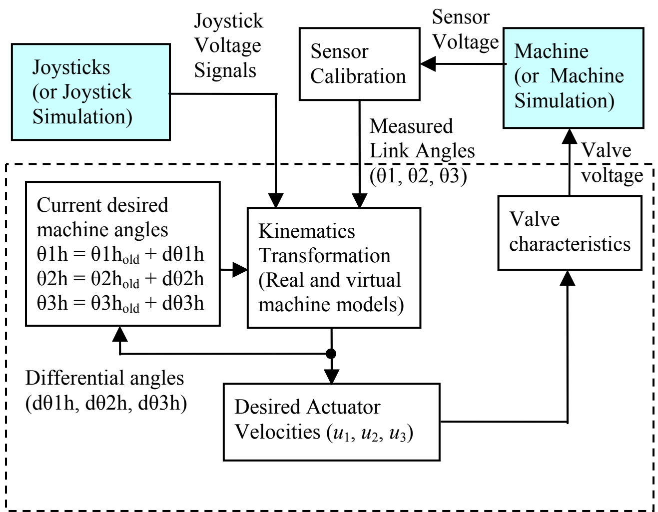

Figure 6: Block diagram for Control Kinematics.

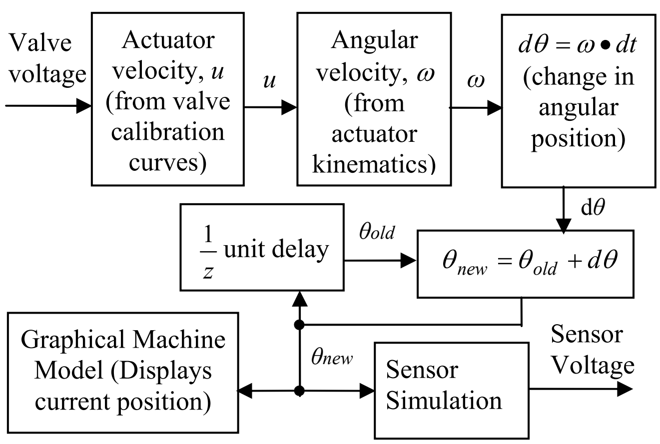

Figure 7: Block diagram for Machine model.

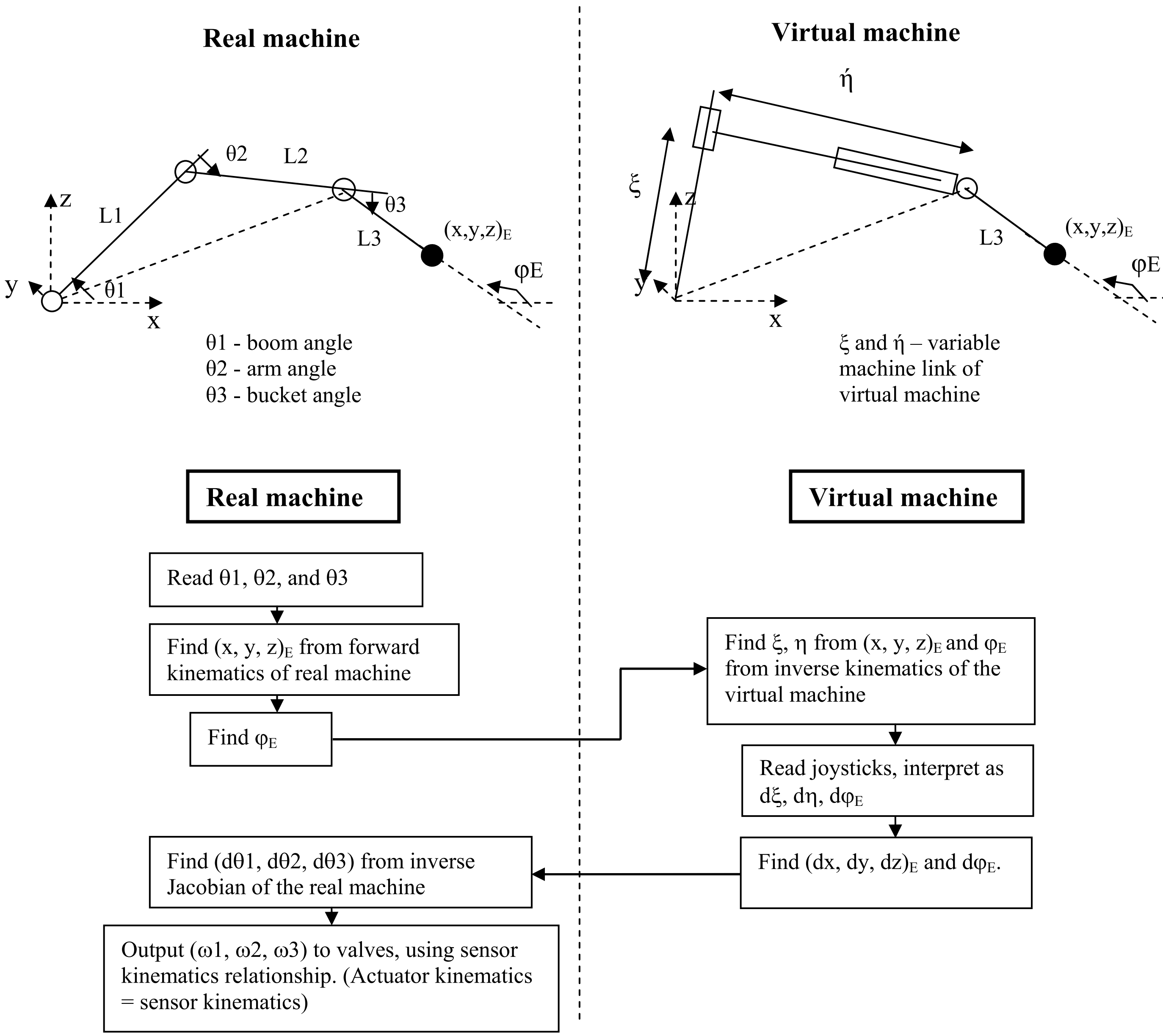

Figure 8: Relationship between Real and Virtual Machine Kinematics

Simulation was run to test the machine response in a Cartesian software kinematics example. The linear trajectory can be generated using different trajectory angles by rotating the x-y-z Cartesian system around a horizontal axis. Examples of the simulation output are shown in Figure 9.

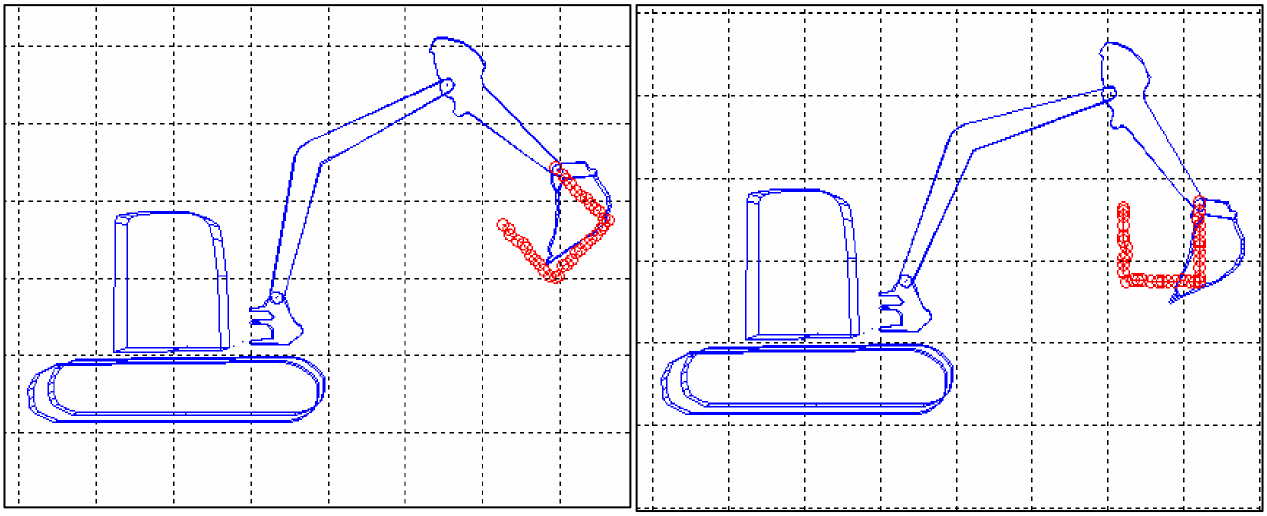

Figure 9: Bucket pin motion control without bucket angle stabilization. Left: Motion in Cartesian coordinates at 45° slope angle. Right: Motion in Cartesian coordinates at 0° slope angle.

The algorithm tested by machine simulation was transferred for controlling the excavator. The machine was moved in its computer-controlled kinematics mode at different slope angles. Figures 11 and 13 show actual measured bucket pin trajectories without stabilizing the bucket angle with the new improved sensor and valve calibration. Figures 10 and 12 show trajectories from preliminary experiments with a roughly calibrated machine, for comparison. The experiments were performed with open-loop control in Cartesian coordinates with coordinated linear motion. An improved version of the machine simulation has been created for code testing. The new simulation is implemented in Simulink to allow seamless transition of new control code and algorithms between simulation and machine. This reduces debugging time and eliminates possible code errors introduced in translation between Matlab and Simulink, prior to implementation on the machine.

Figure 10: Motion in Cartesian coordinates at 45° slope angle. Bucket pin motion control without angle stabilization with **roughly calibrated machine**.

Figure 11: Motion in Cartesian coordinates at 45° slope angle. Bucket pin motion control without angle stabilization with **improved machine calibration**.

Figure 12: Motion in Cartesian coordinates at 0° slope angle. Bucket pin motion control without angle stabilization with **roughly calibrated machine**.

Figure 13: Motion in Cartesian coordinates at 0° slope angle. Bucket pin motion control without angle stabilization with **improved machine calibration**.

B.3 Machine Hardware Mounting

Mounting brackets were designed and constructed for the machine's control electronics, and the control computer, interface box, and other experimental machine hardware was installed onboard the machine. The new hardware is shown in Figures 14-16. (Previously much of this equipment was operated on a small cart outside the machine for improved accessibility during testing and debugging.) Machine wiring was cleaned up and simplified. A power supply system and an automatic safety enable signal for the machine's computer mode, is being designed to allow this equipment to be safely powered from a switched 12V supply obtained from the machine's electrical system.

This ensures a proper power up sequence since the control computer requires a few seconds to "boot-up" after the power is turned on.

Figure 14: Sensor connection junction box

Figure 15: Control computer and interface box hardware

Figure 16: Interface box from operator's perspective

B.4 Machine Tests

Recent machine tests with closed-loop control show improvement in performance compared with earlier tests performed with open-loop control. Work is ongoing to develop and test additional control algorithms in an attempt to further improve the machine performance.

B.5 Three-Dimensional Analysis of Machine Tests using a Stereo Camera Setup

The machine tests conducted have been analyzed in three dimensions using APAS (Ariel Performance Analysis System [3]) and a two-camera setup. In order to accomplish this, control points visible from both cameras were placed around the test area in 3-D. The camera and control point locations are shown in **Figure** 17, and the control points are shown in **Figure** 18.

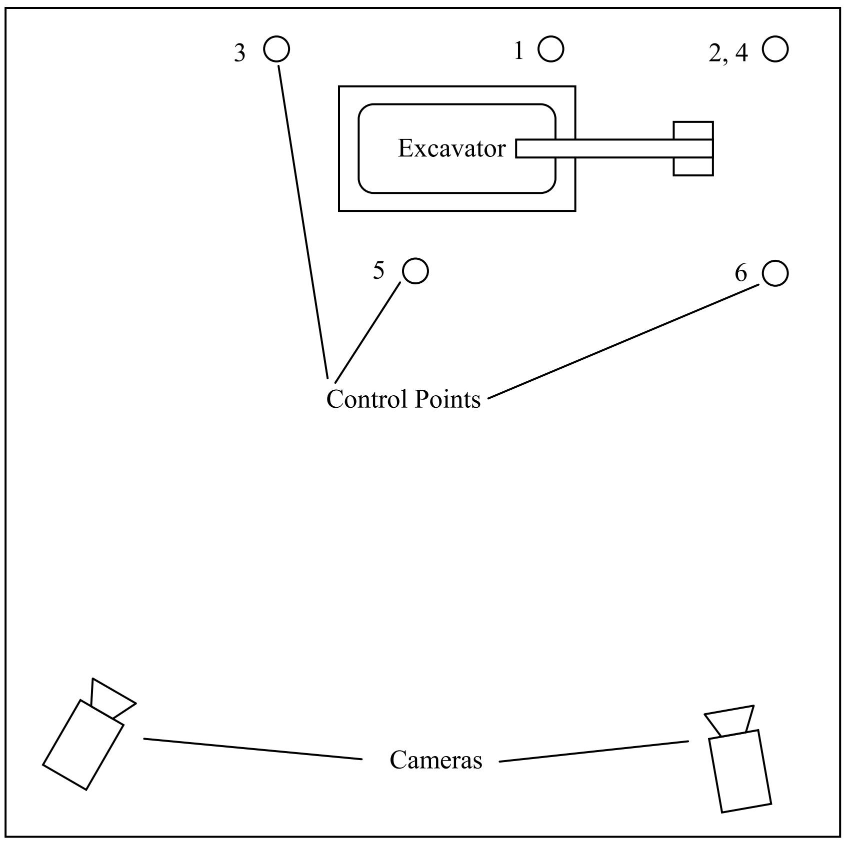

Figure 17: Camera and control point locations for machine tests

Figure 18: Locations of 6 control points establishing coordinate system for 3-D machine test analysis

B.6 Three-Dimensional Analysis and Abstraction of Mine Data

Three-dimensional analysis of mine data, and associated data abstraction was performed. The mine data is in the form of video data collected from three cameras positioned around the shovel. An example of the video data is shown in

Figure19. This data is used below to calculate example bucket trajectories.

Figure 19: Mine data video from three cameras around shovel #112

3-Dimensional Bucket trajectories were calculated using APAS. These trajectories represent the loading of one truck using a Hitachi EX3500 shovel [4] with seven complete digging cycles. The coordinate system for these trajectories was constructed with the x-axis parallel to the base of the shovel (the base does not rotate during this analysis), the y-axis perpendicular to the base of the shovel and the z-axis vertical; the point (0, 0, 0) is located at the center of the base-cab turntable.

B.7 Publications and Recognition

- A utility patent application entitled "Coordinated Joint Motion Control System with Position Error Correction" was submitted on Jan 18th 2006.

- A pre-print paper was recently included on the pre-print CD of the 2006 SME Annual Meetings, St. Louis MO.

- The SME 2005 pre-print paper has been accepted for publication in the SME Transactions.

- Another paper entitled "Digging Trajectory Analysis using Camera Vision" is being submitted to the International Federation of Automatic Control for publication related to the Workshop for Automation in Mining, Mineral and Metal Industry (IFAC-MMM'2006).

C. Results & Discussion

Tool motion trajectories or trajectory elements that can be coordinated by the operator conveniently and efficiently in a transformed coordinate system were defined as kinematics reconfiguration-type category. The projections of bucket trajectories (obtained using APAS) in the x-y (viewing from above the shovel), x-z (viewing from the side of the shovel) and y-z (viewing from in front of the shovel) planes are shown in Figures 20, 21 and 22, respectively. The characteristics of special "repetitive truck loading" curvilinear coordinate systems might be determined from the recorded trajectories. The coordinate transformation equations will be determined to relate the machine's original revolute coordinate system to a curvilinear "repetitive truck loading" coordinate system in which the motion control is natural. This means that the motion can be executed mainly with one velocity control joystick by the operator, while correction and deviation from the one-joystick control can still be made with the other joysticks, but with minimum control movement. These trajectories are for a single point on the bucket, however, multiple points on the bucket were tracked using APAS and would be used to provide additional information on bucket angle as well as position during these trajectories.

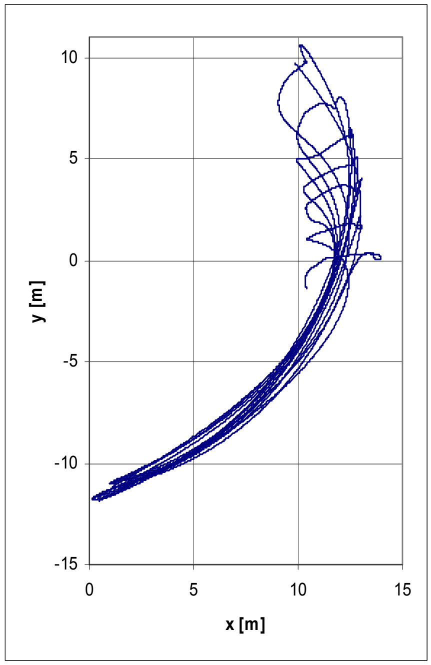

Figure 20: Sample bucket trajectories calculated using APAS viewed from above the shovel

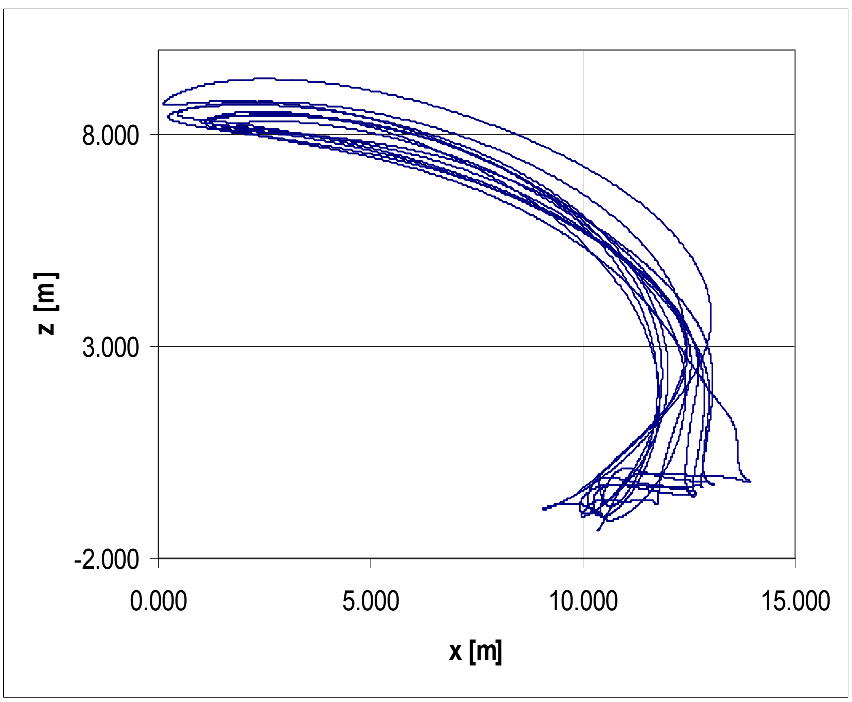

Figure 21: Sample bucket trajectories calculated using APAS viewed from the side of the shovel

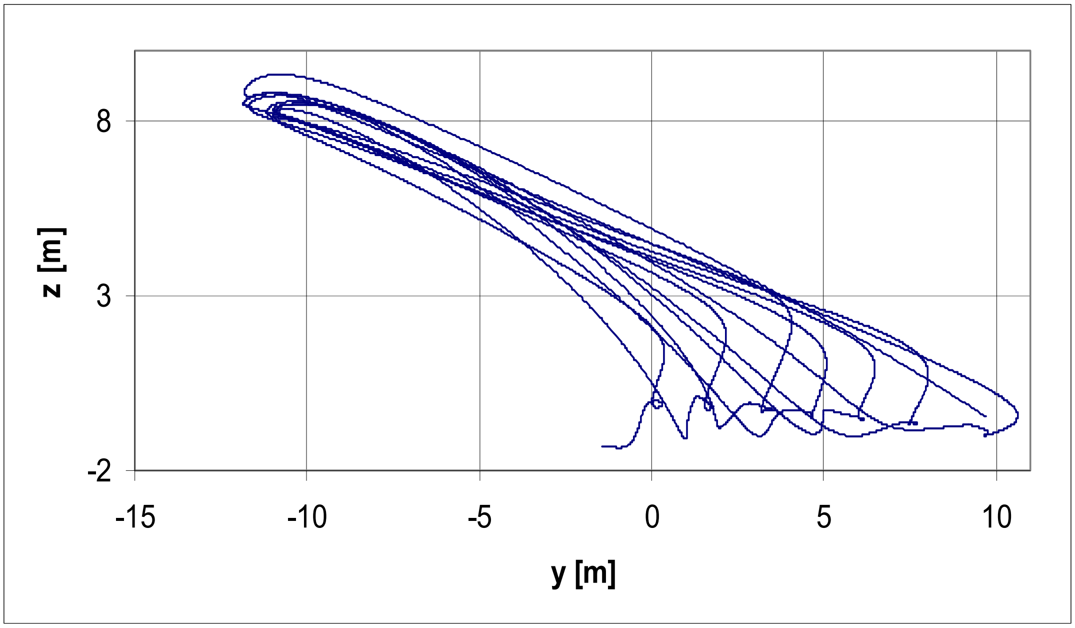

Figure 22: Sample bucket trajectories calculated using APAS viewed from in front of the shovel

The control algorithm was tested on the machine with no feedback correction. Machine tests showed a significant improvement in the linearity of the trajectory with improved sensor and valve calibration (see Figures 10 through 13), though there is no significant improvement in the trajectory angles. Closed-loop control correction was applied to overcome valve distortions and other noise affecting the system. Recent test results are shown in figures 23 through 25. These results show well the improvement over the open loop performance. Square trajectories evaluated using the 2 camera setup is shown in Figures 26 and 27. The observed trajectories demonstrate that the machine's Cartesian kinematics transformation example is performing well.

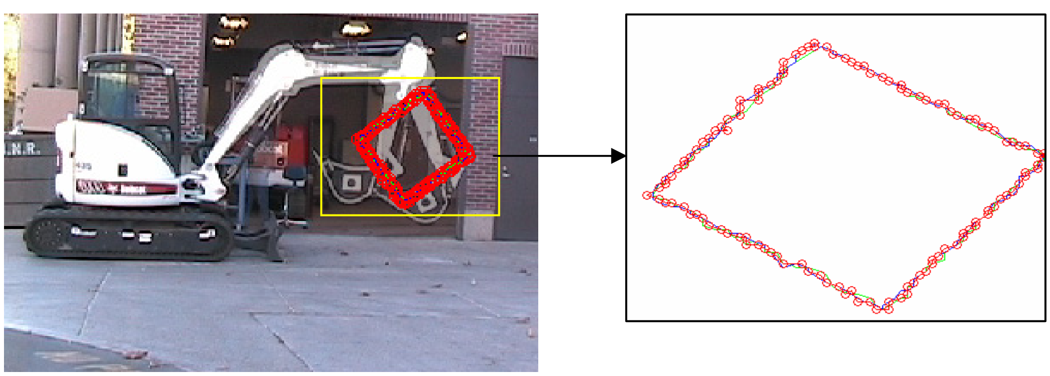

Figure 23: Motion in Cartesian coordinates at 45° slope angle. Bucket pin motion control without angle stabilization with feedback control. Three consecutive cycles are shown.

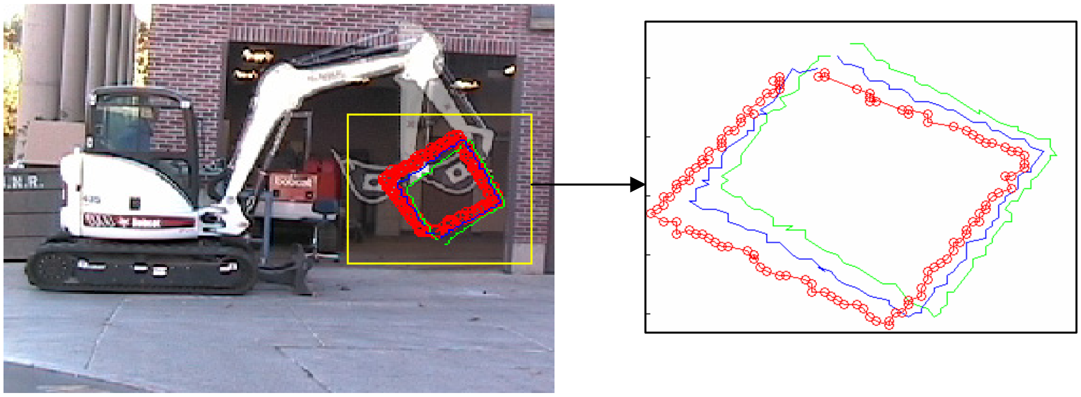

Figure 24: Motion in Cartesian coordinates at 45° slope angle. Bucket pin motion control without angle stabilization with open-loop control. Three consecutive cycles are shown.

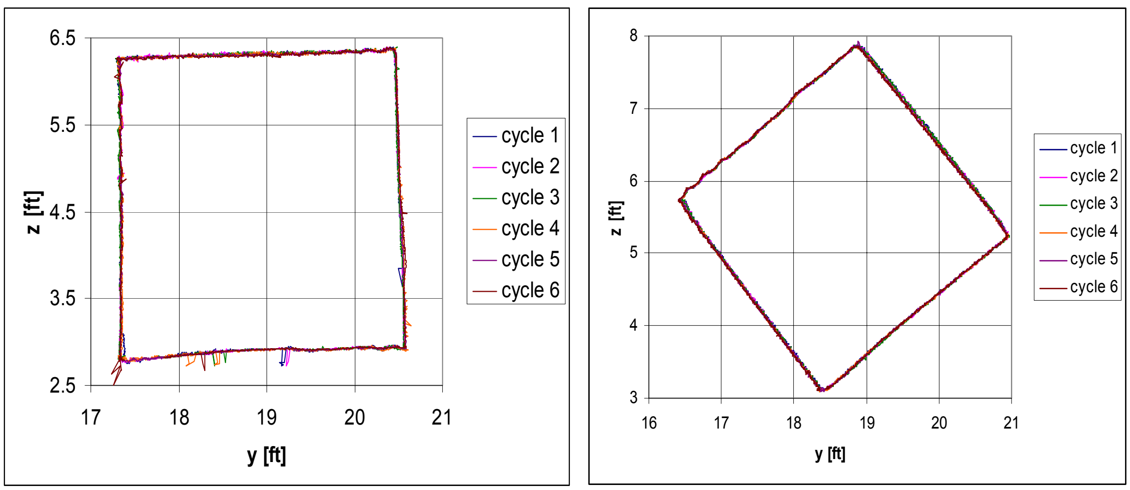

Figure 25: Motion in Cartesian coordinates at 0° and 45° slope angle. Bucket pin motion control without angle stabilization with feedback control. Each trajectory shown consists of 6 consecutive cycles analyzed using APAS.

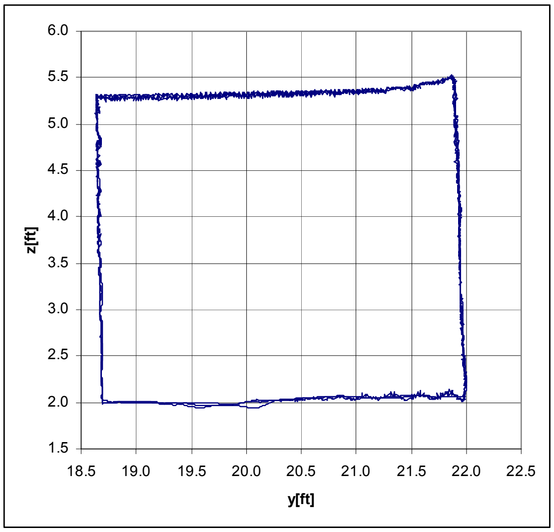

Figure 26. Cartesian Kinematics Transformation Test: Three Successive Bucket Pin Trajectories Processed using 3-D APAS Analysis with 2 cameras (EXAMPLE #1)

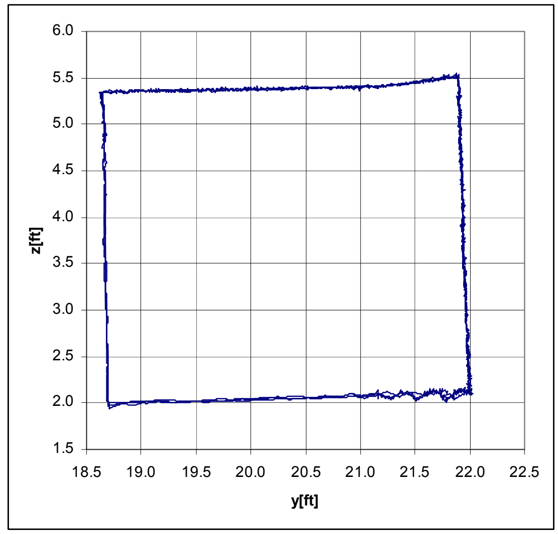

Figure 27. Cartesian Kinematics Transformation Test: Three Successive Bucket Pin Trajectories Processed using 3-D APAS Analysis with 2 cameras (EXAMPLE #2)

Sensor voltage outputs were related to the angle of boom, arm and bucket. Figures 28 to 30 show the results obtained from our model based fitting algorithm that processed the video images of the excavator for joint angles. Different positions were recorded with changes in all three angles. Three sensor voltages were measured via manual readings of three multimeters corresponding to the three machine joint angles. The advantage of this method was that all three machine angles were simultaneously evaluated using our model based algorithm. In an attempt to improve/verify the accuracy of the previously measured empirical calibrations, the actuator kinematics and sensor calibration functions were derived analytically using machine geometry and factory sensor calibration data. The analytical calibration curves obtained for the sensors were similar to the curve shown in Figure 28-30. However, due to the complexity of the bucket geometry and the resulting sensitivity to small measurement errors, the analytical calibration did not match the empirical model as closely as for the boom and arm calibrations.

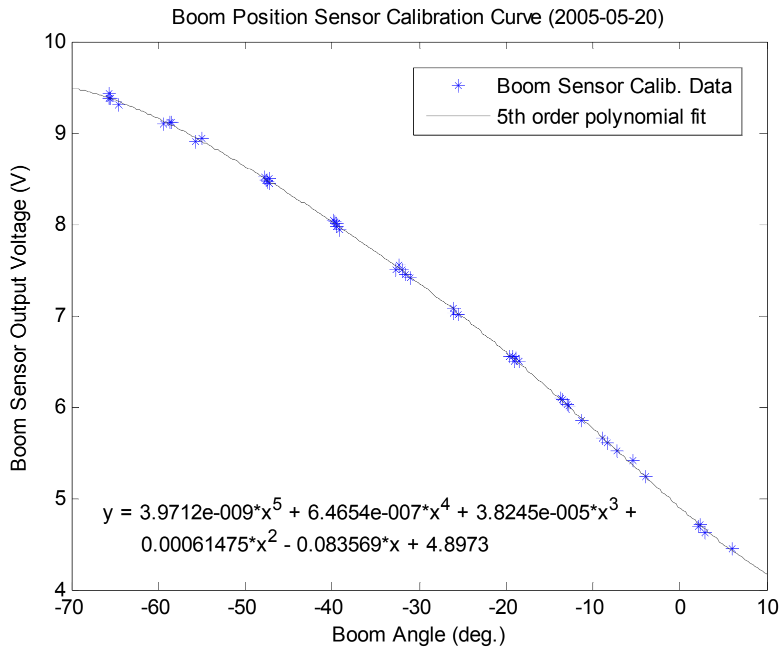

Figure 28: New Sensor Calibration Curve for Boom

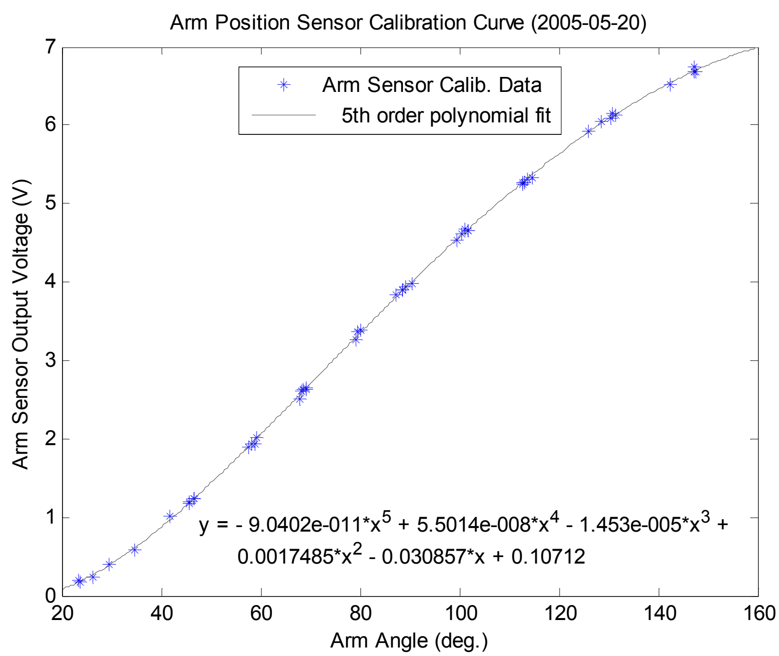

Figure 29: New Sensor Calibration Curve for Arm

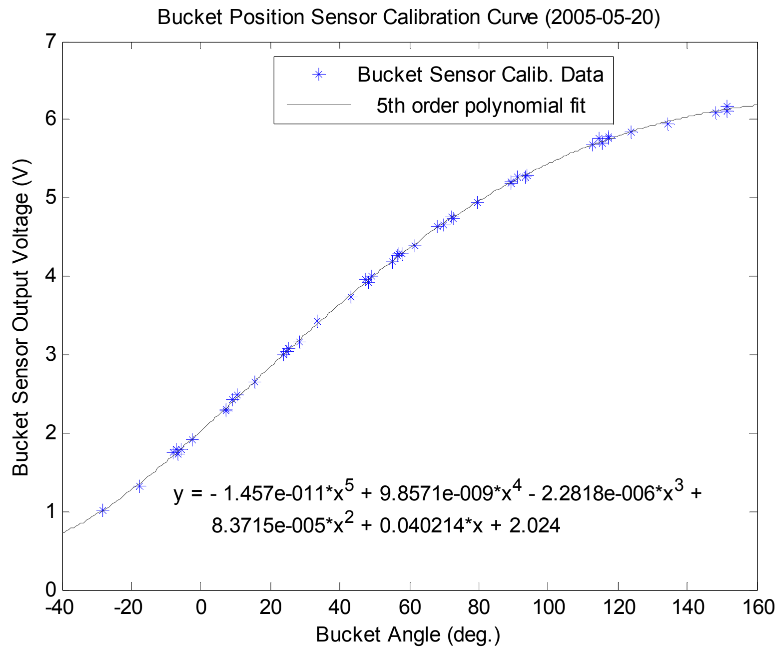

Figure 30: New Sensor Calibration Curve for Bucket

Another test was performed to verify the sensor calibration through data acquisition. The results of the verification test showed that the system appears to be accurate within a fraction of an inch when the error is measured in machine workspace coordinates (see Figure 31-32). This error appears to be acceptable for the application in the research project.

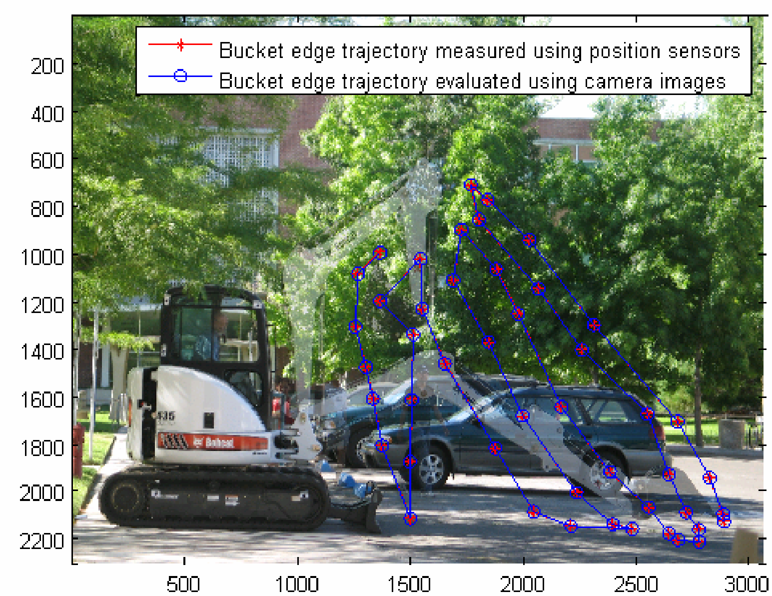

Figure 31: Comparison of sensor-based and vision-based bucket edge trajectories

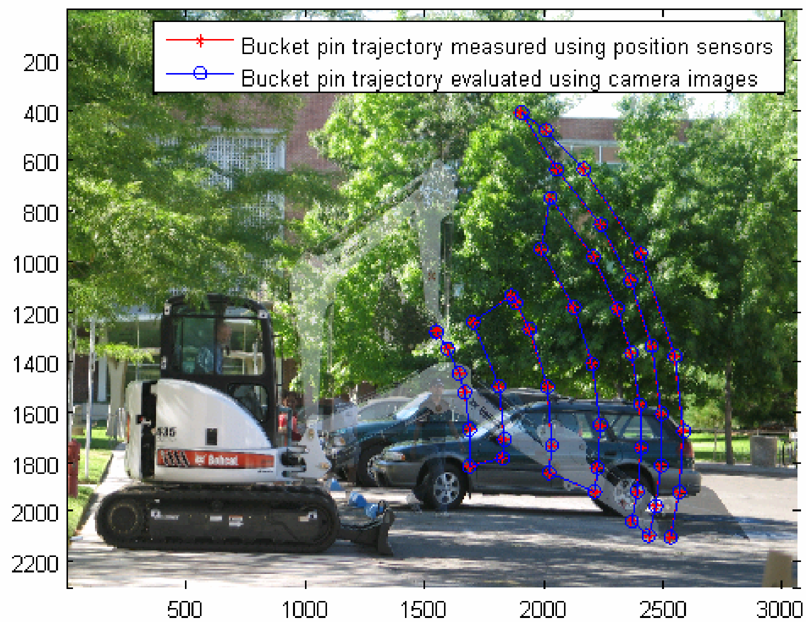

Figure 32: Comparison of sensor-based and vision-based bucket pin trajectories

Electro-hydraulic valves in the experimental excavator were also recalibrated by utilizing the computer interface to the machine. These recalibrated curves were used in the control algorithm for obtaining better machine control. The re-calibrated valves performed quite well, although somewhat differently than expected from their control specifications. The difference might be caused by the fact that these calibration curves included not only characteristics of the electro-hydraulic valves, but also the characteristics of the hydraulic system as well.

D. Conclusion

The 3-D mine data analysis results show that the path of the bucket changes in a fairly systematic and predictable way as the digging face is advanced. For each successive bucket load, the bucket is positioned just next to the previous digging location and returns to the same location above the truck. Aside from this systematic change, the bucket trajectories remain very similar with little change in either the digging cut or the swing. This feature provides the basis for abstracting the typical digging/loading trajectories into a family of curves that in turn, defines a virtual machine kinematics in which the digging task can be performed easier and better by the operator, after optimization by the control computer.

The software-generated machine kinematics was tested in simulation with success. Various controller designs were implemented and simulation was used to test control dynamics prior to implementation on the machine.

The conclusion of the re-calibration is that the valves are performing quite well, although somewhat differently than expected from their specifications. The difference may be caused by the fact that the measured calibration curves include not only characteristics of the electro-hydraulic valves, but also the characteristics of other parts of the hydraulic system as well. Various machine test results, both with open-loop and closed loop-control, provided promising results for further tests.

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